# BELT ASSEMBLY MONITORING SYSTEM

This invention relates to monitoring systems and in particular to systems for monitoring the condition of pulley and belt assemblies. The term "pulley and belt assembly" as used herein is intended to include any kind of assembly where an elongate flexible member ("belt") is driven around two or more rotatable members ("pulleys"), whether for the purpose of delivering rotational drive from one shaft to another or for the purpose of conveying items such as parcels or letters.

The invention provides a method of monitoring a pulley and belt assembly, comprising the steps of applying an external excitation to a span of the belt, detecting vibrations of the said span and/or of another span or spans of the belt, and identifying from said detected vibrations the resonant frequency of one or more of the belt spans, whereby to derive information about the condition of the belt and/or a pulley or pulleys in the assembly.

The invention also provides apparatus for monitoring a pulley and belt assembly, comprising means for imparting an external excitation to a span of the belt, means for detecting vibrations in the said span and/or in another span or spans of the belt, and means for identifying from said detected vibrations the resonant frequency of one or more of the belt spans, whereby to derive information about the condition of the belt and/or a pulley or pulleys in the assembly.

The invention further provides a method of monitoring a pulley and belt assembly, comprising the steps of detecting vibrations in two or more spans of the belt, and comparing the detected vibrations whereby to derive information about the condition of the belt and/or a pulley or pulleys in the assembly.

By way of example, embodiments of the invention will now be described with reference to the accompanying drawings, in which:

Figure 1 is a typical pulley and belt assembly incorporating a monitoring system according to the invention,

Figure 2 illustrates typical plots of amplitude of sensed vibrations against frequency,

Figure 3 illustrates typical plots of amplitude of sensed vibrations against time,

Figure 4 shows an actual plot of the frequency spectrum of transverse vibrations of a moving belt,

Figure 5 shows an actual plot of the frequency spectrum of transverse vibrations of a moving belt when subjected to an impulse,

Figure 6 shows the resulting plot when the plots of Figures 4 and 5 are combined, and

Figure 7 is a plot of belt resonance frequency against belt velocity,

In the assembly seen in Figure 1, a belt 10 is trained to move around two pulleys, a drive pulley 11 and a driven pulley 12. An exciter device 13 is arranged to introduce a controlled vibration into a span S1 of the moving belt (here, the tight span). The exciter device 13 here is in the form of a reciprocable piston 14, operated by a solenoid. The device 13 is arranged such that when the piston 14 extends, it will strike the belt 10 and thus impart an impulse causing the belt span to oscillate transversely. When a belt span vibrates in this way, the tension of the span fluctuates with a frequency twice

that of the transverse oscillations. Vibration sensors 15 and 16 are arranged near the belt 10 so as to detect vibrations in the belt in its tight span S1 and slack span S2 respectively. A data processing unit 17 is arranged to receive signals from both sensors 15 and 16.

It has been observed that when a belt is being driven around a set of pulleys, vibrations of the belt in one of its spans are transmitted to the next span. If a belt span is vibrating, its tension will vary with time, and hence the strain in the length of belt running onto a pulley will be variable. This pattern of strain is stored in the length of belt on the pulley until it runs off into the next span. As it does so, the stored strain pattern in the belt causes tension variations, which excite vibrations in the next span. These are then transmitted to the next span, and so on. The vibrations transmitted in this way become attenuated as they pass from one belt span to the next. Furthermore, the transmitted vibrations in each successive belt span are out of phase with the vibrations in the preceding span, in particular, their phase is delayed. The system shown in Figure 1 can be used to exploit this phenomenon and gather information about the assembly, in particular the belt and pulleys.

The tension of a moving belt can be determined if the resonant frequency of the belt is known. There are many frequency components present in the transverse vibrations of a moving belt, however, from potential sources such as pulley eccentricity or sensor noise, as well as belt resonance frequency and related harmonics. The key, therefore, is to be able to make sense of all these indications in the frequency spectrum.

Figure 2 shows a typical plot of the frequency spectrum of transverse vibrations of the moving belt in the Figure 1 assembly. This plot has been derived from signals received from the sensors 15 and/or 16 using a known Fast Fourier Transform (FFT). As will be seen, the plot exhibits a number of peaks, with the highest being at around 34Hz. It cannot be assumed that this

is the resonant frequency of the belt. In fact, this peak in this example is attributable to the frequency of pulley rotation, which happens to be close to a harmonic of the belt resonance frequency.

Figure 3 shows a plot of the frequency spectrum of transverse vibrations of the same moving belt, only this time after an external excitation in the form of an impulse from the exciter device 13 has been applied to the belt. Again, the plot has been derived from signals from the sensors 15 and/or 16 using the same known FFT. The peaks in this plot again require careful interpretation.

If the Figures 2 and 3 plots are combined, a further plot results which can be seen in Figure 4. In the Figure 4 plot, there are now just two significant peaks. The first, at around 11 Hz, corresponds to the belt resonance frequency and the second, at around 33 Hz, represents the third harmonic. This takes advantage of the fact that the belt's natural frequencies of vibrations are more excited by the input of an impulse to the system than by other potential sources within the system.

Two sources of noise have to be taken into account when trying to extract information about belt resonance frequencies : noise from belt vibrations that correspond to belt resonance frequencies and noise from other sources (the so-called stochastic component) that does not so correspond, for example, from pulley rotation or sensor noise. The extraction algorithm described above is able to eliminate sources of vibration such as pulley rotational frequencies. The presence of sensor noise will not affect the resonance frequency extraction, so long as there is a high enough signal to noise ratio.

If an impulse is imparted by the exciter device 13 to the belt 10 at span S1, in the Figure 1 assembly, this will induce vibrations in the span S1, which will have a peak at the resonant frequency of the span. These vibrations in the belt 10 will be transmitted via pulley 11 to the other span S2, attenuated and phase

delayed. Again, for the transmitted vibrations in the belt 10 in span S2 there will be a peak at the resonant frequency of that span. This information can be extracted by the data processing unit 17 from a comparison of the signals received from the two sensors 15 and 16 and using the combined frequency spectrum technique described above.

Figure 5 shows typical plots of the combined frequency spectrum of vibrations present in belt span S1, as detected by sensor 15 (plot (a)) and the vibrations present in belt span S2, as detected by sensor 16 (plot (b)), when subjected to an impulse by exciter device 13. In each case, there is a distribution of vibrations at various frequencies, indicating a range of different "noises", including "background noise". In each case, however, there is a recognisable peak $f_1$. The peak in plot (a) represents the resonant frequency of span S1 and the peak $f_2$ in plot (b) the resonant frequency of span S2. These can be used to calculate the tension of the belt in each span, since the resonant frequency of a belt span is proportional to its tension (on the same principle as the tension of a guitar string determines its pitch), and the span velocity.

Figure 6 shows typical plots of vibrations detected in belt spans S1 and S2 by sensors 15 and 16 over time (plots (c) and (d) respectively), when subjected to an impulse by exciter device 13.

Plot (c) shows, in addition to vibrations from "background noise", vibrations induced in belt span S1 by the impulse from exciter device 13. The impulse strikes the belt at time $t_0$. Plot (d) shows the vibrations detected in belt span S2. There is again a certain amount of "background noise". There are also, however, the vibrations transmitted from belt span S1 deriving from the impulse. These transmitted vibrations are less than in span S1 and occur somewhat later, ie they are attenuated and phase delayed.

"Background noise" in assemblies such as these will exist partly from vibrations induced in the belt from extraneous sources, for example, through vibrations in the frame of the machine of which the belt and pulley assembly forms part. It should be possible to detect "background noise" of this kind, because it will generally tend to affect each span equally and the vibrations will normally be in phase. Therefore, the data processing unit 17 can be set up to filter out such "background noise" signals.

There may be elements of "noise" introduced into the belt spans by vibrations from the pulleys themselves. For example, if the drive pulley 11 in Figure 1 is slightly eccentric or its bearings are wearing out, it could impart vibrations to the belt 10 as it runs around the pulley. These vibrations will appear in span S2 initially and again in span S1 subsequently, although in an attenuated and phase delayed form. If these particular signals from the two sensors 15 and 16 can be identified, they can then be compared and an analysis used to produce information about the vibrations being input from the drive pulley. This may in turn be used to derive information about the condition of the pulley.

It will be appreciated that the exciter device 13 could be used to impart repeated impulses to the belt at a chosen frequency, for example to enable the belt to be continuously monitored. The particular frequency used for this purpose will preferably be chosen so that the resulting vibration signals will stand out as prominently as possible from the detected "background noise", in order to facilitate their identification and analysis. The device 13 could be arranged with its piston 14 permanently in contact with the belt 10 and deliver to the belt a sinusoidally-varying impulse. The frequency of such an excitation would be chosen to induce in the belt vibrations at or around the resonant frequency of the span.

It will be appreciated that it is not essential to have a sensor to detect vibration at every belt span in an assembly. Using the transmitted vibration theory,

placing at least one sensor at a suitable position may be sufficient to infer vibrational information in other spans.

The resonant frequency corresponding to a given belt tension decreases as the velocity of the belt increases. This is a factor that must be accounted for when measuring belt tension whilst a belt is online.

This phenomenon is highlighted in the theory of axially moving materials. A known mathematical model takes into consideration belt velocity and tension to calculate belt resonance frequency. One of the possible benefits of such a model is that it may be used to determine the significance of any change in resonant frequency when measuring the tension of a particular belt driven at a certain velocity. The model is especially relevant when attempting to monitor the tension of moving belts in mail sorting machines, for example, which use many different specifications of belt. The effect may be negligible for some types of belts, but more pronounced in others.

The model has been validated on a test rig using a belt from a letter sorting machine and the results are shown in Figure 3.

As can be seen, there is a close match between the belt resonance frequencies predicted by the model and the actual resonant frequency of the moving belt. The relatively poor fit between the model and experimental data at the top of the curve is due to the resolution of the FFT used to extract the actual belt resonance frequency information.

The model also shows that at a belt velocity of approximately 3 metres/second, there is a 4% difference between the resonant frequencies of a moving belt and a stationary one. If the stationary value were to be used when calculating the tension in the moving belt, this would lead to an error of 8% in the measurement.

One of the practical advantages of the monitoring systems described above is that they allow the possibility to monitor the condition of pulley and belt assemblies with a minimum number of sensors. This may be important if the assembly has a long belt and numerous pulleys and/or where some of the belt spans are inaccessible.

The system can also be used to monitor torque, because the difference in belt tension between adjacent spans is a measure of torque at the intervening pulley.